Power Line Communication Networks for Large-Scale Control and Automation Systems

Gerd Bumiller[1], Lutz Lampe[2], and Halid Hrasnica[3]

[1]iAd GmbH, Germany, [2]University of British Columbia, Canada, [3]Eurescom GmbH, Germany

Email: gerd.bumiller@iad-de.com, Lampe@ece.ubc.ca, hrasnica@eurescom.eu

Abstract

Power line communications (PLC) uses the existing power line infrastructure for communication purposes. While the majority of recent contributions have discussed PLC for high data-rate applications like Internet access or multimedia communication serving a relatively small number of users, in this article we are concerned with PLC as enabler for sensing, control, and automation in large systems comprising of tens or even hundreds of components spread over relatively wide areas. Typical examples of such systems are energy management and facility automation systems. We provide a discussion of the communication network requirements common to such systems and present transmission concepts for PLC to make use of the existing infrastructure resources, i.e., power lines, to meet these requirements.

I. Introduction

Already during World War II power lines have been considered as a means for data transmission [1]. The main usage of power line communications (PLC) has been by electricity companies for sending control signals at low rates and in several home automation products. It was only recently, spurred by the deregulation of the telecommunication and energy market in the late nineties, that communication over power lines has received a wider attention and is perceived by many as viable alternative or valuable complement to other wired or wireless communication systems.

This is particularly true for Internet access and indoor local area networks (LANs), where application of so-called broadband PLC is considered. Broadband PLC assumes service provision for multimedia applications consuming larger data rates and serving a limited number of users, and its new popularity is evidenced by two special issues on PLC-based LANs and access networks in this Magazine in 2003 [2], [3] and the recent developments in the standardization for high-speed PLC systems within the IEEE [4].

The single main advantage of PLC over other wired communication solutions is the existence of a power line infrastructure. This, for example, allows electricity companies to retrofit their power line networks for communication purposes at little additional costs. In fact, the energy distribution grid is perhaps the most ubiquitous infrastructure worldwide, and its extremely high penetration opens the door for a plethora of applications supported by PLC. Alongside the aforementioned applications, especially the use of PLC for advanced energy management has experienced a strong boost. Examples for this trend include the recently completed research and development project Real-time Energy Management via Powerlines and Internet (REMPLI), which involved nine partners from five European countries and was funded by the European Union (see `www.rempli.org`), and the PoweRline Intelligent Metering

Evolution (PRIME) project launched by the Spanish electric utility Iberdrola and joined by industrial partners from Europe and the U.S., whose aim is the specification of an open and non-proprietary PLC-based telecommunications architecture that "could meet the future requirements on customer real time interfacing and smart grid evolution" (see `www.iberdrola.com/suppliers/SmartMetering` for a White Paper). More generally, the ubiquity of power distribution lines renders PLC an excellent candidate for industrial command-and-control and facility automation systems, in which a common communication network connects a large number of devices that are spread over a wide area. We will collectively refer to such systems as large-scale control and automation systems in the following.

The design and performance requirements for PLC in large-scale control and automation systems are decidedly different from those for PLC in access or indoor systems. Different network parameters such as geographical coverage or number of network nodes and different application-related features such as size of data packets or maximal response time make it necessary to apply different transmission concepts. In the first part of this article, we describe these requirements and derive the necessary features of an enabling PLC network (Section II). This will be followed by a description of transmission techniques that have been developed for such PLC networks in the past few years, e.g. [5]–[9] (Section III). We focus on the physical and medium-access control layer techniques, which are closely linked to the use of PLC as communication technology. The gist of our discussion is that conceptually fairly simple single-frequency networking together with flooding of messages are attractive methods for large PLC networks. While such an approach has been advocated for in wireless ad hoc networks [10], we submit that is suited also for PLC networks (with no mobility) to enable service guarantees. To support this observation, we finally present a quantitative comparison of flooding and routing based on performance parameters specifically relevant to the considered application scenarios (Section IV). Most of the presented material originates from work conducted for energy management systems, under the umbrella of REMPLI, and airfield ground lighting automation systems. Therefore, even though we keep the ensuing description generic in most parts, we will repeatedly refer to these two specific applications.

II. Control and Automation Systems Using PLC

We start by considering the two mentioned application examples for large-scale control and automation systems to motivate that PLC is a very attractive solution and to concretely show what is required of a PLC network.

A. Application Examples

1) Energy management systems: The energy management system of the future foresees the implantation of considerable intelligence into the distribution grid which essentially renders it a situation-aware network of interconnected sensors and actuators. These intelligent grids of tomorrow have gained global attention under the label "smart grids" [11]. The realization of the smart grid concept entails the existence of a reliable communication network, which likely integrates several communication carriers. Due to the inherent availability of power lines as carriers and the resulting advantages with respect to installation costs, we expect that PLC will play a prominent roll in the implementation of smart grids.

Let us consider a few typical examples of smart grid functionalities to illustrate the requirements for the communication network. The first example is real-time pricing to balance energy consumption and moderate peak loads.

The key components for real-time pricing are intelligent energy meters and the possibility of communication with a central data collection and control station. Assuming that every household is equipped with such a meter, the PLC network between meters and the common transformer station can include easily 300 nodes or more. If the PLC network extends beyond the transformer station and to the medium-voltage layer, the network size can grow into the thousands of nodes. Fast access to individual meters is also needed to enable advanced customer services. For example, in a recent tender a Dutch electric utility required that their call center can access 90% of all meters within five seconds. In Germany, the national regulator Bundesnetzagentur considers the possibility of real-time switching between electric utilities, and the vendors of billing software work on solutions for customers to find the presently least-expensive provider. Again, fast access to meters is an important element for these solutions.

Another smart-grid functionality is the management of energy distribution using a supervisory control and data acquisition (SCADA) system. SCADA sensors permanently monitor the grid load and report to a control center, from which open/close commands are sent to switches to adapt the distribution structure to the dynamics of energy generation and consumption. Such operations become more frequent with increasing decentralization of energy generation and they need to be executed reliably and in real time in order to maintain grid stability. Thus SCADA imposes strong reliability and real-time requirements on PLC.

2) Airfield ground lighting automation systems: Modern airfield ground lighting (AGL) automation systems enable individual lamp control and monitoring of sensors deployed at airfields. Such functionalities are needed to meet the latest recommendations by national and international regulators to enhance safety of aircraft ground movement and to aid visual guidance systems. Figure 1 illustrates a typical wiring topology of an AGL system. Devices such as lamps and microwave sensors are arranged in a ring structure of typically between 3 km to 15 km and connected to a constant-current supply via transformers.

PLC is a cost-effective and elegant solution to enable communication between the airport tower and the ground lighting system, particularly for existing airport infrastructures where build-up of new dedicated communication networks would be expensive. The communication network has to bridge considerable distances and also connect across power-electric components, especially transformers, which are not designed for high-frequency communication signals. In terms of signal flow, we note that all data communication needs to go through a central node which is directly connected to the tower (see Figure 1). Furthermore, the reaction time, i.e., the round-trip delay of a signal between the tower and a lamp, is critical. Since the communication channels are time variant, the PLC system needs to permanently monitor the communication quality to all network nodes to guarantee a certain maximal reaction time. The time variance of the channels is due to different current steps of the regulator, variable loads in the circuit, crosstalk from other rings which often run parallel over several kilometers, and even weather conditions. Hence, the PLC system needs to be sufficiently robust with respect to channel variations. In addition, a node failure must not affect communication to other nodes. Hence, redundant signal paths between the central and the other network nodes are mandatory for the PLC network.

B. Requirements for the PLC Infrastructure

The described application examples are representative in that the PLC network needs to connect a large number of devices like switches, sensors, meters, or lamps that are distributed over a relatively wide area. In the following, we attempt to categorize the typical requirements for the PLC infrastructure in order to support large-scale control and automation systems.

1) Network coverage and data flow: Application protocols for metering, automation, facility or grid management support point to multi-point communication with mainly short data packets. Automation and grid management systems have mainly a master-slave structure, because these applications are strictly hierarchically organized. In facility management client-server networks are becoming popular. A client polls the server (data point) or the server pushes the data periodically. In metering applications, both strictly hierarchical and client-server structures are used. All applications have in common that the devices of the system represent the communication nodes of the PLC network, and each of these nodes needs to be connected to the central node (master, server). This requirement is challenging considering that many network nodes are remote from the central node, and perhaps serve time-critical applications like those mentioned in the previous section. Furthermore, while individual nodes communicate only small amounts of data at a time, the total data volume to be transferred through the network is substantial. Hence, resource-efficient transport of data to and from the central node is mandatory to achieve sufficient network coverage.

2) Robustness to changes: In PLC networks the communication channel may change abruptly during normal operation. For example, switching operations in medium-voltage energy systems to balance the power consumption over the distribution grid will result in changes of channel transfer functions in sizeable parts of the PLC network. The PLC network design must be able to cope with such abrupt changes, which means that the connectivity must be maintained during or quickly recovered after these changes. Since severe network disruptions due to, e.g., physical removal of network links, are often not exceptional events but do occur frequently during normal operation, maintenance of system availability is only possible with (i) redundant communication links and (ii) autonomous use of redundancies. That is, a PLC network that needs to estimate link qualities and to re-establish connections after topology changes occurred will not be able to fulfill reliability requirements. Instead, ad hoc networking features are needed. It is important to note that also the removal and addition of network nodes, or changes in the impedance of the associated device affect the communication channels in a large neighborhood around this node. This behavior is very different from wireless communications, where the mere presence or absence of a wireless device does not affect the link quality for another device.

3) Quality-of-Service (QoS): The main QoS requirements for the PLC network in control and automation systems are high communication reliability, high overall network throughput, and strict limits on delay. Often messages transmitted from nodes to the central node, e.g., notification about a sudden voltage drop, or from the control center to network nodes, e.g., a switching command for an actuator, are time critical. Failure to meet delay requirements can have serious consequences with often human safety at stake. In addition, due to the time variance of the communication channels, the functionality of all network nodes needs to be verified continuously to guarantee reliable data transfer and system response time. Since optimization of throughput, reliability, and delay pose often conflicting demands on the design of the communication protocol, management of QoS requirements is a non-trivial task.

III. Transmission Concepts for PLC

We now present transmission concepts apt to meet the need for network coverage, link redundancies, and guaranteed QoS outlined above.

A. Single-Frequency Network (SFN) Concept

The spatial dimension of the PLC network renders direct communication between the central node and all other network devices infeasible. To still achieve complete coverage, messages need to be repeated, which is also known as multihop transmission or relaying. Considering that PLC re-uses an existing infrastructure and the broadcast nature of the PLC channel, an altruistic repeater concept is appealing. That is, network nodes that overhear a message for another destination are prepared to retransmit this message. Such a repeater concept makes optimal use of the available communication nodes in the network and is flexible enough to ensure network coverage and communication reliability also under changing channel conditions and topologies. In particular, the use of multiple repeaters to relay the same message signal provides redundant signal paths, which are needed to minimize network outages. To manage this multi-relay transmission with a minimum use of communication resources, the single frequency network (SFN) concept, which has been known from macrodiversity wireless communication systems [12], can be applied. The SFN allows all repeaters to transmit simultaneously using the same frequency band. The next receiving node(s) sees a linear superposition of the retransmitted signals, which is indistinguishable from a single signal being sent over an equivalent multipath channel. Hence, any communication technique suitable for transmission over multipath channels can be applied in an SFN. One popular method is orthogonal frequency division multiplexing (OFDM) [5], [12]. We note that SFN-PLC transmission benefits from signal enhancement due to concurrent retransmission. In some cases, destructive interference may occur, which can be mitigated using distributed space-time coding concepts presented in [8].

B. Flooding Concept

If altruistic relaying is used to route a message through the network, then the flooding concept is implemented. We submit that flooding is an attractive packet delivery process in control and automation PLC networks for the following reasons. First, flooding eliminates almost all routing overhead, which can be substantial for large networks with multiple repeater levels. Second, it is extremely robust to network changes. This is crucial for applications such as energy management or AGL systems. As mentioned above, changes in PLC networks are often abrupt and affect a large fraction of nodes. The need to establish a route would compromise communication reliability and delay constraints. Third, considering the delivery of a single packet, flooding minimizes the delay in that it always finds the "shortest" path to the destination. Key for flooding to be effective is the application of the SFN concept. SFN transmission avoids congestion for the packet that is flooded and thus accomplishes efficient use of network redundancy and minimizes transmission delay.

On the downside, flooding has the potential to create closed communication loops and to massively occupy channel resources. Furthermore, different packets which are flooded simultaneously in a specific geographical area can destroy each other. To avoid or mitigate these effects, two measures are suggested. First, active network nodes (repeaters) monitor the packets or packet numbers and ensure that every packet is repeated only once. Second, each packet is equipped with a counter n_{repeat} that specifies the maximal number of times a packet can be repeated before it reaches the destination, and this counter is decremented during each repetition. We note that two different counters may be used for transmission in opposite directions due to potentially non-reciprocal transfer functions or different interference situations at different locations.

C. Mixed Deterministic and Random Medium Access Control (MAC) Concept

As we have discussed in Section II, a feature common to many applications is that traffic flows to and from a central node, which suggests a centralized medium access control (MAC) with a master-slave concept. The organization of the transmission in the downlink direction (from master to slaves) is simple since only the master transmits data to one or multiple slaves.

The situation is different for the uplink, where a number of slaves may have data to be transmitted to the master at the same time. A first option would be a purely deterministic MAC protocol that completely eliminates signal collisions. To this end, slaves could be successively polled by the master to see whether uplink resources are required. To ensure a certain polling rate, which defines the reaction time of the PLC network, a certain fraction of channel uses has to be reserved for this mechanism. For example, consider a sensor which monitors rare events that occur on average, say, once every day, but which require a fast response time of, say, 10 seconds. The master would have to poll the sensor every 10 seconds, which is an excessive waste of resources. Furthermore, while this approach may be feasible in relatively small networks, the reaction time can quickly become unacceptably large for networks with hundreds of nodes. For the same reasons, other deterministic medium access policies, such as master-slave oriented bus protocols, token ring protocols, or solutions with fixed time-slots reserved for each individual network node within a time division multiple access (TDMA) scheme are also not well suited. Random medium access techniques, such as Aloha or carrier-sense medium access (CSMA), offer more flexibility in this regard. Since reliable carrier sensing in PLC is complicated by the hidden node problem [13], particular collision avoidance techniques have to be employed like those developed for indoor PLC systems [14]. However, application of mechanisms for solving the hidden node problem and collision avoidance add considerable overhead for transmission with small data packets and therefore they are not well suited for automation and control PLC systems. In case of purely random access without collision avoidance, i.e., Aloha or slotted Aloha, the packet delay can become unacceptably large and network throughput is limited in the case of highly loaded networks with a large number of nodes.

These considerations motivate a hybrid MAC protocol which combines elements of deterministic and random medium access. First, the master establishes a network-wide TDMA frame structure through the broadcast of control packets to all nodes. Within each frame the master allocates time slots for dedicated master-slave connections serving services such as polling. Then, the remaining time slots are used for random medium access in the uplink, which allows slaves to connect spontaneously with the master, e.g., if an event which deserves quick reaction from the master is detected or if a slave joins the network. For the sensor-example mentioned above the master would poll the sensor in regular intervals much larger than the response time to ensure that the sensor is functional and synchronized to the TDMA frame structure. When the sensor has an event to report, it uses random access within the dedicated uplink frame to send the message. Considering that per-node link utilization is not high, slotted Aloha, or one of its variants, is the method of choice for the random access within the TDMA frame structure. Since all network resource control rests with the master, it dimensions the frame structure in accordance with the QoS demands from the specific applications served by the network. Furthermore, two mechanisms due to SFN-based flooding work in favor of random access with slotted Aloha. First, as long as at least one repeater node receives a signal originated from another node successfully, the underlying message is not annihilated even though signal collisions may have occurred. Secondly, SFN transmission can be exploited to reduce the waiting time between retransmission attempts and thus improve overall transmission delay applying the concept of local acknowledgments devised in [7].

D. Remarks

We would like to remark on some of the challenges associated with the described SFN-based flooding concept.

1) Synchronization: SFN-based flooding requires a network wide clock. This can be established through the TDMA structure, which is maintained by broadcast packets sent by the master. Every packet is equipped with a synchronization preamble [9] based on which a slave adjusts its timing. Since broadcast packets serve several purposes (see also Section IV-B below), they are sent regularly. Experiments have shown that timing synchronization with an accuracy of very few (often fewer than two) symbol intervals is easily achieved, which also means that only very little additional guard space between transmissions is required for an SFN. We note that frequency synchronization is not problematic due to the low carrier frequencies used in narrowband PLC.

2) Channel Estimation and Error Propagation: The need for receiver-side channel estimation in SFN-based flooding can be bypassed using differential modulation, e.g., across sub-carries if OFDM is applied. Likewise, the effect of error propagation can be neglected assuming the use of error detection, such that only nodes which deem a packet as received correctly will retransmit it.

3) Channel Occupation and Energy: Clearly, there is a price to be paid for not needing a route. First, redundant retransmissions occupy channels unnecessarily and prevent other messages to be sent. When one TDMA frame travels, no other frame can travel in a certain geographical area, i.e., spatial reuse and thus packet origination rate are limited. Second, the use of many retransmissions wastes energy, which, e.g., undermines the purpose of “smart” grids. These problems are mitigated through flooding using counters as described above. Variations of flooding which aim at reducing the number of redundant broadcasts, cf. e.g. [15], can further remedy the situation. Since the location of many network devices are static, topology information may be used during flooding. For example, in parts of the network with high connectivity, only a subset of nodes relays a message. Furthermore, signal waves can be directed towards the destination, which also increases multiplexing capability. However, topology information needs to be exploited with care as, for example, in ring topologies found in medium-voltage energy distribution grids or AGLs (see Figure 1), a single node failure can completely change the direction into which the signal wave needs to propagate to reach the destination.

IV. Numerical Results: Flooding vs. Routing

To make the argument for SFN-based flooding more concrete, in this section we provide numerical performance results for three specific criteria pertinent to large-scale PLC networks. We compare flooding with the alternative of centralized proactive routing, for which every message is only retransmitted by exactly one repeater node at every repetition level and the route is determined at the master node based on link quality information, namely packet error rate (PER).

A. Average Duration of a Polling Cycle

Polling is often one of the fundamental network operations. For example, in AGL automation it is critical to continuously monitor the functionality of all devices and thus the master frequently polls all slaves (see Section II-A).

The average duration of the polling cycle $\bar{D}$ is defined as the average time the master needs to complete a single packet-request-response service with every slave. An analytical expression for a lower bound for $\bar{D}$ for the case of routing systems can be obtained by making the idealized assumption that the instantaneous PERs for all node-to-node links are available at the master. To obtain an analytical expression for $\bar{D}$ for the flooding-based system we assume that the maximal number of packet retransmissions, n_{repeat} (see Section III-B), is chosen such that $\bar{D}$ is minimized. Furthermore, we have simulated SFN-based flooding using an adaptation method for n_{repeat}.

Table I shows the numerical results for $\bar{D}_{\mathrm{rout,opt}}$ assuming optimal routes, $\bar{D}_{\mathrm{flood,opt}}$ assuming optimal n_{repeat}, and $\bar{D}_{\mathrm{flood,adapt}}$ with adapted n_{repeat} for a ring topology (see Figure 1) with 10 and 100 uniformly distributed nodes, and for a randomly generated tree topology with 100 and 200 nodes, respectively. The latter are illustrated in Figure 2. For SFN-based flooding we distinguish two scenarios for superposition of simultaneously relayed signals, namely aggregation of signal energies from all signal paths (denoted by energy combining (EC) in Table I) and selection of the individual channel with the largest energy (denoted by energy selection (ES)).

The figures in Table I are the average duration of a polling cycle measured in number of time slots. We observe that flooding consistently achieves a lower polling cycle duration than routing. This is due to the fact that with flooding the packet is received via the optimal route and via additional repeater paths, and thus the probability of successful transmission is increased compared to routing. Furthermore, the restriction of the number of repetitions in flooding due to n_{repeat} avoids unnecessary occupation of channel resources. We further observe that performance degradations due to in-situ adaptation of n_{repeat} are less than 4%.

B. Duration of a Broadcast Transmission

In the considered PLC networks messages are frequently broadcasted from the master to all slaves. The purpose of broadcast messages is manifold. It serves, for example, to update the TDMA frame structure, to inform slaves of which slots are used for specific services and physical-layer parameters, to download software updates, or to transmit fast time-varying application-specific parameters such as the distance of an approaching airplane in AGL automation systems.

Flooding is a natural fit for fast broadcast transmission as it utilizes the very broadcasting nature of the PLC channel. The duration of a broadcast is simply $\max\{n_{\mathrm{repeat}}\}$ times the duration for a downlink slot. In case of routing, we assume that the master sends the broadcast message to a number of slaves selected such that the union of all nodes that receive the message transmitted along those routes forms the complete set of nodes. In this way, the address field of the broadcast packet is not expanded compared to a unicast packet. To minimize the duration of the broadcast, we apply a greedy algorithm that selects the next slave such that a maximal number of nodes is reached along its route.

Table II shows the time needed to deliver a broadcast message with routing and flooding for the same four network topologies considered for polling. The time is measured in number of time slots, and the particular figures were determined such that the PER for all slaves is less than 0.1%. It is interesting to observe that performance differences between flooding and routing are moderate for ring structures, whereas they become significant for tree topologies. In particular, flooding is rather insensitive to the underlying topology since signal waves propagate in all directions. Likewise, the actual number of nodes is insignificant as long as the spatial extension of the network does not change significantly.

C. Robustness to Topology and Channel Fluctuations

We have already pointed out earlier that the quality of communication links in a PLC network can vary with time due to, e.g., load changes. Switching operations even change the network topology. A typical example for a severe topology change would be the opening of a medium-voltage distribution line ring structure at a location close to the master node.

To illustrate the agility of flooding, we simulated polling cycles for 100 nodes which first were arranged in a ring structure and after a certain number of cycles rearranged into a random-tree structure. We hasten to say that such a dramatic topology change is unrealistic and only serves as an extreme academic example to test the robustness of flooding. In the simulations, a request to a slave was repeated until the master successfully received a response. Figure 3 shows the measured duration for a polling cycle, where the network topology is changed before cycle number 1. We observe that before the topology change the duration of the polling cycle jitters around average values of about 410 (EC case) and 425 (ES case) time slots. The length of the polling cycle jumps to about 700 (EC) and 780 (ES) slots right after the network change, but it is already reduced again by about 250 slots in the following cycle. Already after 5 to 7 polling cycles the cycle durations have converged to the (new) stationary values. To have an estimate for the length of the adaptation process in absolute time we assume a slot duration of 10 ms. This value is typical for PLC transmission in the CENELEC-A band with a bandwidth of 50 kHz. Then, the average duration of a polling cycle for 99 slaves would be between 4 and 4.5 seconds according to the results in Figure 3. The first polling cycle after the abrupt topology change would require 7 to 8 seconds to successfully reach all slaves, but within only 30 to 40 seconds the adaptation to the new topology is completed. This very fast adaptation, which is only possible with an algorithm with short memory, satisfies real-time requirements for the communication system in, e.g., smart grid applications even during and after a switching instant. Hence, SFN-based flooding is a very attractive solution also in this regard.

V. Conclusions

In this article, we have presented an overview of the requirements for PLC to become an enabler for advanced control and automation systems such as energy management or facility automation systems. Starting from these requirements we have described suitable PLC transmission concepts. We have advocated, and in part substantiated with numerical evidence, that the combination of single-frequency networking with flooding embedded into a hybrid MAC protocol is attractive to meet the application requirements. The efficacy of the presented concepts has been verified in field trials under the umbrella of the REMPLI project, and PLC products based on this technology are currently being used in a number of pilot projects for advanced meter management (e.g. in Karczew, Poland) and street-light control (e.g. in Fürth, Germany). We close by noting that the future proliferation of PLC as enabler for smart-grid functionalities is not only a technological issue, but it also depends strongly on how swiftly electric utilities are able to implement necessary changes in the energy distribution process and ongoing legislatory developments concerning infrastructure reliability and new services like real-time pricing.

References

[1] H. Ferreira, H. Grove, O. Hooijen, and A. Vinck, *Power Line Communication*, ser. Encyclopedia of Electrical and Electronics Engineering, Edited by J. Webster. New York: John Wiley & Sons, Inc., pp. 706-716 1999.

[2] H. Latchman and L. Yonge (Guest Editors), "Power Line Local Area Networking," *IEEE Commun. Mag.*, vol. 31, no. 4, Apr. 2003.

[3] S. Galli, A. Scaglione, and K. Dostert (Guest Editors), "Broadband is Power: Internet Access Through the Power Line Network," *IEEE Commun. Mag.*, vol. 31, no. 5, May 2003.

[4] S. Galli and O. Logvinov, "Recent Developments in the Standardization of Power Line Communications within the IEEE," *IEEE Commun. Mag.*, vol. 46, no. 7, pp. 64–71, Jul. 2008.

[5] G. Bumiller, "Single Frequency Network Technology for Medium Access and Network Management," in *International Symposium on Power Line Communications and Its Applications (ISPLC)*, Athens, Greece, Mar. 2002.

[6] ——, "Power-Line Physical Layer Emulator for Protocol Development," in *International Symposium on Power Line Communications and Its Applications (ISPLC)*, Zaragossa, Spain, Mar. 2004.

[7] L. Do, H. Hrasnica, and G. Bumiller, "SALA MAC Protocol for PLC Networks Based on Single Frequency Network Technique," in *IEEE International Symposium on Power Line Communications and Its Applications (ISPLC)*, Orlando, FL, USA, Mar. 2006.

[8] L. Lampe, R. Schober, and S. Yiu, "Distributed Space-Time Block Coding for Multihop Transmission in Power Line Communication Networks," *IEEE J. Select. Areas Commun.*, vol. 24, pp. 1389–1400, Jul. 2006.

[9] G. Bumiller and L. Lampe, "Fast burst synchronization for power line communication systems," *EURASIP J. Adv. in Signal Processing, Special Issue: Adv. Signal Processing and Computational Intelligence Techniques for Power Line Commun.*, vol. 2007, Article ID 12145.

[10] A. Scaglione and Y.-W. Hong, "Opportunistic large arrays: Cooperative transmission in wireless multihop ad hoc networks to reach far distances," *IEEE Trans. Signal Processing*, vol. 51, no. 8, pp. 2082–2092, Aug. 2003.

[11] E. Garrity, "Getting Smart," *IEEE Power Energy Mag.*, vol. 9, pp. 38–45, Mar./Apr. 2008.

[12] M. Eriksson, "Dynamic Single Frequency Networks," *IEEE J. Select. Areas Commun.*, vol. 19, pp. 1905–1914, Oct. 2001.

[13] M. Mushkin, "A Novel Distributed Synchronized Media Access Control Mechanism and Its Applicability to In-House Power-Line Networking," in *International Symposium on Power Line Communications and Its Applications (ISPLC)*, Malmö, Sweden, Mar. 2001.

[14] M. Lee, R. Newman, H. Latchman, S. Katar, and L. Yonge, "HomePlug 1.0 Powerline Communication LANs - Protocol Description and Performance Results," *Intl. J. Commun. Systems, Special Issue: Powerline Commun. and Applications*, vol. 46, no. 5, pp. 447–473, Jun. 2003.

[15] T. Kwon, M. Gerla, V. Varma, M. Barton, and T. Hsing, "Efficient Flooding with Passive Clustering — An Overhead-Free Selective Forward Mechanism for Ad Hoc/Sensor Networks," *Proc. IEEE*, vol. 91, no. 8, pp. 1210–1220, Aug. 2003.

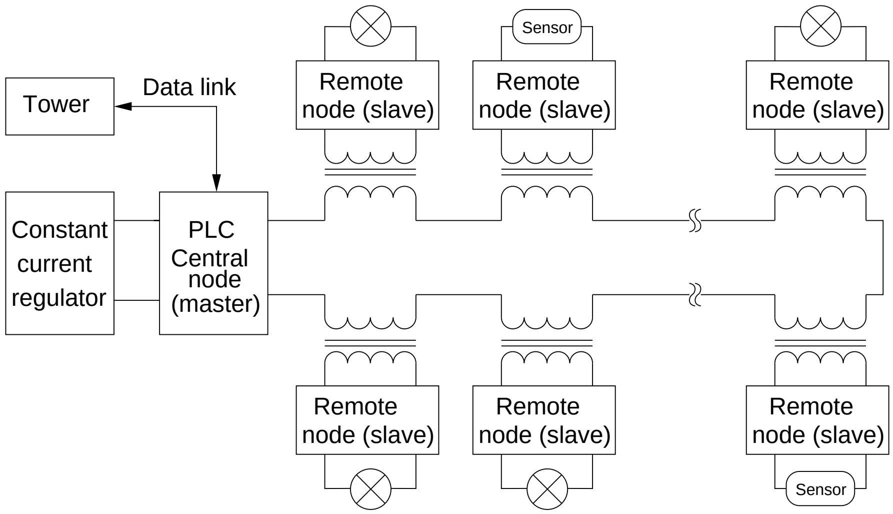

Fig. 1. Illustration of the ring structure of an airfield ground lighting automation system. A typical ring has a length of between 3 to 15 km and includes between 10 to 200 remote nodes (lamps, sensors).

TABLE I

COMPARISON OF THE AVERAGE DURATION OF A POLLING CYCLE USING OPTIMAL ROUTING AND FLOODING WITH OPTIMAL AND ADAPTED NUMBER OF RETRANSMISSIONS n_{repeat}. DURATION IS MEASURED IN NUMBER OF TIME SLOTS. EC REFERS TO THE CASE THAT THE ENERGIES OF THE MULTIPLE SIGNAL PATHS ARE AGGREGATED AT THE RECEIVER; IN ES ONLY THE INDIVIDUAL CHANNEL WITH THE LARGEST ENERGY IS CONSIDERED.

Channel model	Ring topology		Tree topology	
	10 nodes	100 nodes	100 nodes	200 nodes
$\bar{D}_{\mathrm{rout,opt}}$	30	427	421	1027
$\bar{D}_{\mathrm{flood,opt}}$ (ES)	29	419	387	993
$\bar{D}_{\mathrm{flood,opt}}$ (EC)	28	403	367	939
$\bar{D}_{\mathrm{flood,adapt}}$ (ES)	30	423	393	1003
$\bar{D}_{\mathrm{flood,adapt}}$ (EC)	29	404	368	945

TABLE II

COMPARISON OF THE AVERAGE DURATION FOR A BROADCAST TO ALL SLAVES USING ROUTING AND FLOODING. DURATION IS MEASURED IN NUMBER OF TIME SLOTS.

Channel model	Ring topology		Tree topology	
	10 nodes	100 nodes	100 nodes	200 nodes
Routing	5	8	37	73
Flooding	3	4	5	5

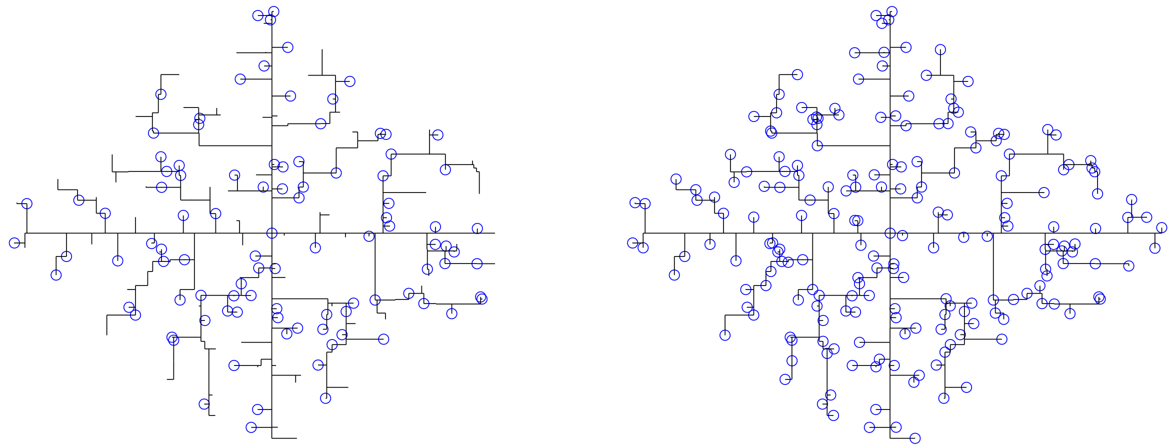

Fig. 2. Tree topology as an example model for an energy distribution grid with 100 (left) and 200 (right) nodes (shown as circles). The x-and the y-axis are the main supply lines to which all nodes are connected. The master is located at the origin and the slave nodes are generated according a uniform distribution over the diamond-shaped area defined by the maximum cable-length between master and slaves, where cables run in parallel to the x- and y-axis. The node density is kept constant regardless of the number of nodes.

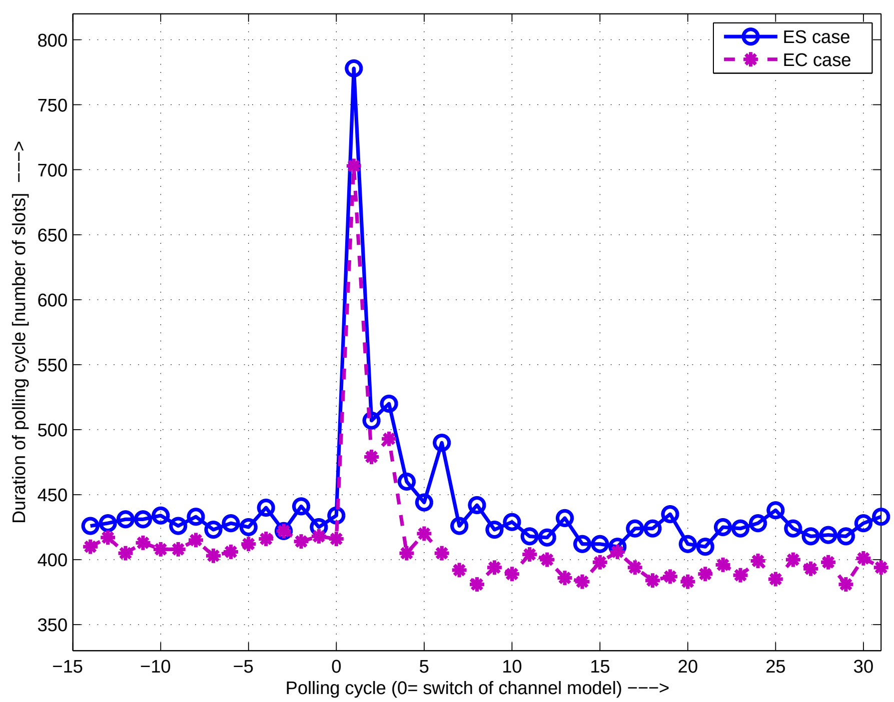

Fig. 3. Duration of polling cycles for flooding before and after an abrupt topology change.